

# Constraints on the Cosmic Structure Formation Models from Early Formation of Giant Galaxies

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## ABSTRACT

A recent observation of Steidel et al. indicates that a substantial fraction of giant galaxies were formed at an epoch as early as redshift  $z > 3 - 3.5$ . We show that this early formation of giant galaxies gives strong constraints on models of cosmic structure formation. Adopting the COBE normalization for the density perturbation spectrum, we argue that the following models do not have large enough power on galactic scales to yield the observed abundance: (i) standard cold dark matter (CDM) models (where mass density  $\Omega_0 = 1$  and power index  $n = 1$ ) with the Hubble constant  $h \lesssim 0.35$ ; (ii) tilted CDM models with  $h = 0.5$  and  $n \lesssim 0.75$ ; (iii) open CDM models with  $h \lesssim 0.8$  and  $\Omega_0 \lesssim 0.3$ , and (iv) mixed dark matter models with  $h = 0.5$  and  $\Omega_\nu \gtrsim 0.2$ . Flat CDM models with a cosmological constant  $\lambda_0 \sim 0.7$  are consistent with the observation, provided that  $h \gtrsim 0.6$ . Combined with constraints from large-scale structure formation, these results imply that the flat CDM model with a low  $\Omega_0$  is the only one that is fully consistent with observations. We predict that these high-redshift galaxies are more strongly clustered than normal galaxies observed today.

*Subject headings:* galaxies: formation-cosmology: theory-dark matter

## 1. INTRODUCTION

Recently Steidel and collaborators (Steidel & Hamilton 1993; Steidel et al. 1996, hereafter S96) have developed a novel technique to detect high redshift galaxies using Lyman continuum break redshifted to the wavelength range between  $U$  and  $G$  pass bands. They have found a number of candidate galaxies having redshift  $z = 3 - 3.5$  in broad-band photometry, and their follow-up spectroscopy has confirmed that these galaxies indeed have such redshifts or at least are consistent with having such redshifts. This observation

indicates that about 2% of the galaxies in the magnitude range  $\mathcal{R}_{AB} = 23.5 - 25$  mag have redshift  $z = 3 - 3.5$ ; this means that a substantial fraction ( $\gtrsim 10 - 30\%$ ) of giant galaxies observed today have already been formed before this redshift. The observed spectrum and colors suggest that the formation epoch of these galaxies could probably be earlier by  $\Delta t \simeq 1$  Gyr. S96 have also argued from the equivalent widths of saturated absorption lines that the velocity dispersion of these galaxies is probably as high as  $180\text{--}320 \text{ km s}^{-1}$ , comparable to that for  $L > L^*$  elliptical galaxies observed today, although the possibility that the dominant part of equivalent widths is caused by P Cygni profile of gas outflows is not excluded. While we have to await the confirmation from future high resolution spectroscopy, it is very likely that they are beginning to observe the early stage of spheroids of giant galaxies.

We note that this abundance information of high redshift galaxies gives a strong constraint on the model of cosmic structure formation. The current structure formation models are always tuned so that they yield successful predictions for the large-scale structure observed at present time. As a result it is difficult to discriminate them by using the information of large scale structure at low redshift alone. On the other hand, the predictions for small-scale structure at an early epoch, such as high-redshift galaxies, are quite different from model to model. We argue that even the present rather premature data on high redshift galaxies can discriminate models, provided that some extra information concerning the normalization of the primordial spectrum is given.

We also show that the models that satisfy the test of the abundance of high-redshift galaxies predict a high degree of bias of these galaxies relative to the mass compared to that of normal galaxies observed today.

## 2. MODELS

We take as a basis of our argument the Press-Schechter formalism (Press & Schechter 1974, hereafter PS), which allows an analytic treatment of the problem. The PS formalism has been tested extensively by  $N$ -body simulations for a variety of hierarchical clustering processes in various cosmic structure formation models (e.g. Bond et al. 1991; Bower 1991; Lacey & Cole 1994; Mo & White 1996; Mo, Jing & White 1996). In the PS formalism, the comoving number density of dark halos in a unit interval of halo velocity dispersion  $\sigma$  is given by

$$\frac{dN}{d\sigma}(\sigma, z) = \frac{-3}{(2\pi)^{3/2}} \frac{1}{r_0^3 \sigma} \frac{\delta_c(z)}{\Delta(r_0)} \frac{d \ln \Delta(r_0)}{d \ln r_0} \left[ \frac{d \ln \sigma}{d \ln r_0} \right]^{-1} \exp \left[ -\frac{\delta_c^2(z)}{2\Delta^2(r_0)} \right], \quad (1)$$

where  $r_0$  is the radius of a sphere that comprises a halo of mass  $M$  for a homogeneous universe with mean mass density  $\rho_0$ , i.e.,  $M = 4\pi\rho_0 r_0^3/3$ ;  $\Delta(r_0)$  is the rms of the linear mass density fluctuations in top-hat windows of radius  $r_0$ ;  $\delta_c(z)$  is the critical overdensity for collapse at redshift  $z$ . The quantity  $\Delta(r_0)$  is completely determined by the initial density spectrum  $P(k)$  (which is assumed to be Gaussian) and we normalize  $P(k)$  by specifying  $\sigma_8 \equiv \Delta(8h^{-1}\text{Mpc})$ , where  $h$  is the Hubble constant in units of  $100 \text{ km s}^{-1}\text{Mpc}^{-1}$ . For any cosmological model and power spectrum, one can calculate  $dN/d\sigma$  given the function  $\delta_c(z)$  and the relationship between  $\sigma$  and  $r_0$ . We take the result summarized by Kochanek (1995; see also Bartelmann et al. 1993) for these relations. As one can see from eq.(1), a change in  $\delta_c(z)$  leads to a proportional change in  $\sigma_8$ .

We consider five sets of cosmic structure formation models, each containing one free parameter for which a constraint is to be derived. The first set is the standard CDM model (where the cosmic density of matter  $\Omega_0 = 1$  and the power index of primordial density perturbation spectrum  $n = 1$ ) with  $h$  a free parameter. The second set is the tilted CDM model with  $h$  fixed but with  $n$  varying. The third one is a CDM model in an open universe (open CDM), with  $\Omega_0$  a free parameter. In the fourth set, we consider CDM model in a flat universe (flat CDM: i.e.  $\lambda_0 + \Omega_0 = 1$  where  $\lambda_0 \equiv \Lambda/3H_0^2$  is the cosmic density parameter of cosmological constant), with  $\Omega_0$  a free parameter. Finally, in the fifth set, we discuss mixed dark matter (MDM) model (where  $\Omega_0 = 1$ ) with neutrino mass density  $\Omega_\nu$  as a free parameter. The model parameters are summarized in Table 1.

For CDM models, the power spectra are calculated using the fitting formulae of Hu & Sugiyama (1996). The contribution of the gravitational wave to the normalization is ignored. We assume the baryon density parameter to be  $\Omega_b = 0.0125 h^{-2}$  from primordial nucleosynthesis calculations (Walker et al. 1991). The amplitudes of the power spectra are estimated from the 4-year COBE data (Bennett et al. 1996) with the aid of the fitting formulae given by White & Scott (1996). For the MDM model, we use the fitting formulae of Ma (1996) to estimate both power spectra and COBE normalizations.

In the calculation of the comoving number density of halos in eq.(1) we need to specify the velocity dispersion of galactic halos and the epoch when these halos are formed. From the equivalent widths of heavily saturated lines, S96 have estimated the velocity dispersions of Lyman break galaxies to be  $\sigma = 180\text{--}320 \text{ km s}^{-1}$ . These values are compared to  $200\text{--}230 \text{ km s}^{-1}$  for  $L^*$  galaxies of E/S0 type. Together with other indications, S96 concluded that they are indeed observing early phase of the spheroids of  $> L^*$  galaxies, although they did not exclude the possibility that this high velocity dispersion is caused by outflow rather than by gravitational motion. Here we accept their interpretation that this velocity dispersion is gravitational, and take the threshold velocity dispersion to be  $\sigma_{\text{min}} = 180 \text{ km s}^{-1}$ . We note

the possibility that the true halo velocity dispersion may be higher than that of stars (e.g., Gott 1977).

We evaluate the comoving number density of galaxies for two epochs: (i) 1 Gyr before the epoch that corresponds to  $z = 3$ , and (ii) at  $z = 3.5$ . Case (i) is probably a more realistic formation epoch for these galaxies, as inferred from the  $\mathcal{R} - G$  color assuming that some star formation activity persists to  $z = 3$ . Case (ii) is true only when star burst is instantaneous: a strong rest-frame UV light implies that the burst epoch is only 0.01 Gyr back from the observed epoch. As noted by S96, this is an unlikely case, since it requires all observed galaxies to undergo completely coeval burst phase at the observed redshift. We take case (ii) as the most conservative estimate.

### 3. RESULTS

The abundance estimate of Lyman break galaxies depends on assumed cosmology. S96 estimated that the comoving number density of these galaxies is  $N_g \approx 2.9 \times 10^{-3} h^3 \text{ Mpc}^{-3}$  in the Einstein-de Sitter universe and  $5.4 \times 10^{-4} h^3 \text{ Mpc}^{-3}$  in an open universe with  $\Omega_0 = 0.1$ . These abundances correspond to 1/2 and 1/10 of the space density of present-day galaxies with  $L > L^*$ , respectively. Shimasaku & Fukugita (1996) have argued, using their evolution model where all spheroidal components are assumed to have formed very early and passively evolved and disk components are added later with e-fold time of 5 Gyr, that S96 are observing basically all E/S0 galaxies at this redshift if the universe is open or  $\Lambda$ -dominated, and that the observed fraction is about 1/3 of what is expected if  $\Omega_0 = 1$ . For our argument here, it suffices to take the value of  $N_g$  given by S96. For cosmologies other than those used in S96, we estimate the density by modifying the comoving volume in the redshift range  $3.0 \leq z \leq 3.5$  into the one for the relevant case.

We should note that what is calculated with eq. (1) is the halo abundance, and that some halos may not contain “galaxies” if star formation is for some reasons inhibited in them. The calculation of Shimasaku & Fukugita indicates that this is unlikely to happen at least for a low density or a  $\Lambda$ -dominated universe. Taking into account the fact that the velocity dispersion of a halo could be higher than that is observed for stars (see discussion in Section 2) and the fact that some massive halos which do not contain Lyman break galaxies may be missed, we take  $N_g$  of S96 as a lower limit to the halo number density calculated with eq. (1).

It is also possible that some massive halos contain more than one galaxies, and the number density of galaxies could be larger than that of the dark halos with velocity

dispersion bigger than  $\sigma_{\min}$ . This possibility is, however, unlikely in the general field, as observed in S96 <sup>1</sup>.

Before considering individual models, let us examine the general sensitivity of our calculation to the parameters discussed above. We plot in Figure 1 the abundances of ‘galaxies’ predicted in the standard CDM model and in a flat CDM model with  $\lambda_0 = 0.9$  as a function of the normalization  $\sigma_8$ . For each model, results are shown for four cases: two cases refer to two extreme values of  $h$ , and one case where  $\Omega_b$  is set to zero for the lower  $h$  case. The other curve shows a somewhat different calculation, where the number density of galaxies is obtained by dividing the mean density of mass contained in halos with  $\sigma \geq \sigma_{\min}$  by a mass corresponding to  $\sigma_{\min}$ . The difference among four curves are not large. The change of  $h$  has two compensating effects: an increase of  $h$  pushes the redshift (for a given  $\Delta t$ ) of halo formation to a higher value and causes  $N$  to decrease, but at the same time enhances the power on small scales for a given  $\sigma_8$  [because  $\Delta(r_0)$  becomes steeper] so as to increase the number density. The net dependence of  $N$  on  $h$  is weak for the ranges of  $h$  relevant to our discussion. The inclusion of the baryonic component suppresses the power on small scales (see e.g. Hu & Sugiyama 1996) and thereby reduces the number density of halos predicted for a given  $\sigma_8$ . The figure shows, however, that the change is small even for low values of  $h$  (and low  $\Omega_0$ ), where the effect is expected to be stronger. The calculation using halo mass also agree with other calculations from equation (1), except for large  $\sigma_8$  where a considerable amount of mass is already in large halos. For the range of  $\sigma_8$  relevant to our discussion, however, the difference can be neglected. Fig. 1 shows that, in any case, the values of  $\sigma_8$  required to give the observed abundance do not depend sensitively on the detail of the calculation, since the predicted curves crosses the observed  $N_g$  (shown as the horizontal lines) where  $N$  increases sharply with  $\sigma_8$ .

Our main results are summarized in Figure 2, which shows the values of  $\sigma_8$  required to give the observed comoving number density of  $N_g$  as a function of the free parameter in specific models listed in Table 1; the two curves correspond to the calculations for the two different epochs, the upper one showing case (i) whereas the lower one case (ii). We also indicate as the thick lines the normalization  $\sigma_8$  given by the 4-year COBE data as a function of  $h$  in panel (a), and for two choices of the Hubble constant,  $h = 0.5$  and  $0.8$ , in panels (b)-(e). Since we take our abundance calculation to give a lower limit on the halo abundance, the allowed range lies in the lower-right region of the line indicating the COBE

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<sup>1</sup>We remark that our result would change little, even if we allow for this possibility: at high redshift the total mass contained in “massive halos” is small. We obtain basically the same result if we take the number density of galaxies to be the ratio between the total density of mass contained in dark halos with  $\sigma > \sigma_{\min}$  and the typical mass implied by the observed velocity dispersion.

normalization.

Let us now discuss each specific case given in Fig. 2. Panel (a) shows the constraint on  $h$  for the standard CDM models with  $\Omega_0 = 1$  and  $n = 1$ . The allowed range is  $h \gtrsim 0.35$  and is not very sensitive to the changes of  $\Delta t$ . This limit is slightly higher than the upper limit  $h < 0.3$  (so that  $\Gamma \equiv \Omega_0 h < 0.3$ ) to give the required large scale clustering power at  $z \sim 0$  obtained from the correlation function on scales near  $10h^{-1}$  Mpc (e.g. Efstathiou, Sutherland & Maddox 1990). For the most standard case of  $h = 0.5$ , the abundance limit gives  $\sigma_8 \gtrsim 0.6$  whereas the COBE normalization leads to  $\sigma_8 \sim 1.2$ . Although there is no conflict between the abundance limit and the COBE normalization, the gap between the two values of  $\sigma_8$  implies that an order of magnitude more halos must have existed at  $z > 3$  without forming stars.

Panel (b) gives the constraint on the power index  $n$  for CDM models with  $\Omega_0 = 1$  and  $h = 0.5$ . We obtain a limit  $n > 0.85$  for  $\Delta t = 1$  Gyr [case (i)]. This limit is relaxed to  $n \gtrsim 0.75$  if we take  $\Delta t = 0.01$  Gyr [case (ii)]. To allow a value  $n \sim 0.7$ , we must take  $h \sim 0.6$  and  $\Delta t \ll 1$  Gyr. On the other hand,  $n \sim 0.7$  and  $h \sim 0.5$  is required to match the observations on large scales at low redshift (e.g. Ostriker & Cen 1996); such a model is, therefore, marginally ruled out from our abundance argument.

Panel (c) shows the results for open CDM models with  $n = 1$ . The predicted abundance depends only weakly on  $h$  and calculations are shown only for  $h = 0.5$ . The values of  $\sigma_8$  for a given  $N$  is almost flat against the change of  $\Omega_0$ . The normalization given by the COBE data, however, depends strongly on  $\Omega_0$ . We obtain a limit  $\Omega_0 \gtrsim 0.5$  for  $h = 0.5$  and  $\Omega_0 \gtrsim 0.3$  for  $h = 0.8$ . These limits are summarized in terms of the shape parameter (of CDM-like power spectrum) as  $\Gamma \gtrsim 0.25$ . The fact that the abundance of  $N_g$  is smaller and the (linear) density perturbations grow slower in an open universe makes the limit on  $\Gamma$  lower than that obtained for the Einstein-de Sitter universe. The limit obtained here is marginally consistent with what is required to explain the large scale clustering power.

Given in panel (d) is the constraint on  $\Omega_0$  for flat CDM models with  $n = 1$  ( $\Omega_0 + \lambda_0 = 1$ ). We present the abundance results for  $h = 0.7$ , but the results depend only weakly on  $h$ . The COBE data leads to a limit  $\Omega_0 \gtrsim 0.4$  for  $h = 0.5$ . For  $h = 0.8$ , the limit is  $\Omega_0 \gtrsim 0.2$ . In terms of  $\Gamma$  the limit is  $\Gamma \gtrsim 0.16$ - $0.2$ . This range of  $\Gamma$  (or  $\Omega_0$ ) well overlaps with the range derived from the clustering of galaxies on large scales. In particular, a flat CDM model with  $\Omega_0 \sim 0.3$  and  $h \sim 0.7$ , as favoured by Ostriker & Steinhardt (1996), is perfectly consistent with the observed abundance of giant galaxies at high redshifts.

The last panel of Fig.2 shows the constraint on  $\Omega_\nu$  for MDM models with  $h = 0.5$  and  $\Omega_0 = 1$ . The MDM model with  $\Omega_\nu = 0.3$  has been found to be successful in predicting the

clustering properties of galaxies on large scales (e.g. Jing et al. 1993; Klypin et al. 1993), but it was later found that this model do not have large enough power on small scales to explain the total baryon mass observed in damped Ly $\alpha$  systems (Mo & Miralda-Escude 1994; Kauffmann & Charlot 1994; Ma & Bertchinger 1994; Klypin et al. 1995). In panel (e) we see that the combined COBE/abundance limit gives much stronger constraint on  $\Omega_\nu$ : if  $h = 0.5$  any MDM models with  $\Omega_\nu \gtrsim 0.2$  are inconsistent with this limit. Lower values for  $\Omega_\nu$  are still allowed, but the advantage of the MDM models in explaining large scale clustering power would be lost for such a small  $\Omega_\nu$ .

#### 4. PREDICTION FOR THE CORRELATION FUNCTION

The bias parameter of dark halos,  $b$ , is defined by the ratio of the two-point correlation function of halos  $\xi$  to that of mass  $\xi_m$  as  $\xi(r) = b^2 \xi_m(r)$ . Mo & White (1996) argued that this bias parameter is a function of velocity dispersion  $\sigma$  at redshift  $z$  and is accurately described (to moderately nonlinear regime) by

$$b(\sigma, z) = 1 + \frac{1}{\delta_c(z)} \left[ \frac{\delta_c^2(z)}{\Delta^2(r_0)} - 1 \right], \quad (2)$$

where  $r_0$  is specified by  $\sigma$  as discussed in Section 2. This  $b$  parameter refers to the bias parameter of galaxies if galaxies were formed at the center of the halos and have not lost their identities during the subsequent evolution.

In Figure 3 we plot  $\sigma_{8,g} \equiv \sigma_8 b$  as a function of  $\sigma_8$  for the ‘Lyman break galaxies’ in flat CDM models, where  $b$  is the average of  $b(\sigma, z)$  over  $\sigma$  with a weight of  $dN/d\sigma$ . According to the above interpretation,  $\sigma_{8,g}$  is the rms fluctuation of counts of these ‘galaxies’ in spheres of radius  $8h^{-1}\text{Mpc}$  at present time. This value should be compared to that for present-day normal galaxies,  $\sigma_{8,g} \approx 1$  (e.g. Davis & Peebles 1983). Fig.3 shows that  $\sigma_{8,g}$  is substantially larger than unity in all cases, implying that ‘Lyman break galaxies’ in these models are significantly more strongly clustered than normal galaxies. For  $\Omega_0 = 0.3$  and  $\sigma_8 \sim 1$ ,  $\sigma_{8,g}$  is about 1.8. Thus the amplitude of the correlation function of these galaxies at present time should be about 3 times as large as that of normal galaxies, or comparable to that of giant early-type galaxies (e.g. Davis & Geller 1976; Jing, Mo & Börner 1991). This prediction corroborates the arguments that the observed Lyman break galaxies are the progenitors of present-day large E/S0 galaxies and is in agreement with the preliminary observational result of Giavalisco et al. (1994).

## 5. CONCLUSIONS

We have demonstrated that the abundance of giant galaxies at high redshift gives significant constraints on models of cosmic structure formation and discriminate among models that satisfy other currently available tests. Using COBE normalization of the density perturbation spectrum, we have shown that the abundance of Lyman break galaxies, as observed by S96, already rules out a number of current models of structure formation. In particular, the CDM models that are devised to give large scale clustering power by lowering the Hubble constant or by tilting the initial density power spectrum are disfavoured, leaving the case with a low density universe as marginally allowed. We are left with the moderately  $\Lambda$ -dominated CDM models as the ones that satisfy all the constraints. We have also shown that the MDM models that can explain large scale clustering power are strongly disfavoured by the same argument.

In this *Letter* we have concentrated only on the tests based cosmic structure formation. There are, of course, constraints from many other observations, such as those on the Hubble constant and on the age of the universe, and those from gravitational lensing observations, that we have not discussed here. It is interesting to note that our favoured “moderately  $\Lambda$ -dominated CDM model” is consistent with all available constraints.

We have also argued that if cosmic large-scale structure forms in hierarchical clustering, high-redshift giant galaxies should be more strongly clustered at present time than normal galaxies, corroborating the interpretation that Lyman break galaxies are progenitors of early-type galaxies.

One caveat is that our argument hinges on the assumption that the velocity dispersion observed by S96 is gravitational, that is, the galaxies they observed are giant galaxies. If the high velocities are dominantly non-gravitational, the conclusions we derived should all be modified, so is the interpretation given in S96. We are very much looking forward to the confirmation of this point in future high resolution spectroscopy. When this doubt is cleared up, even the current, rather premature observational data of high redshift galaxies can serve as an important diagnostics for models of cosmic structure formation.

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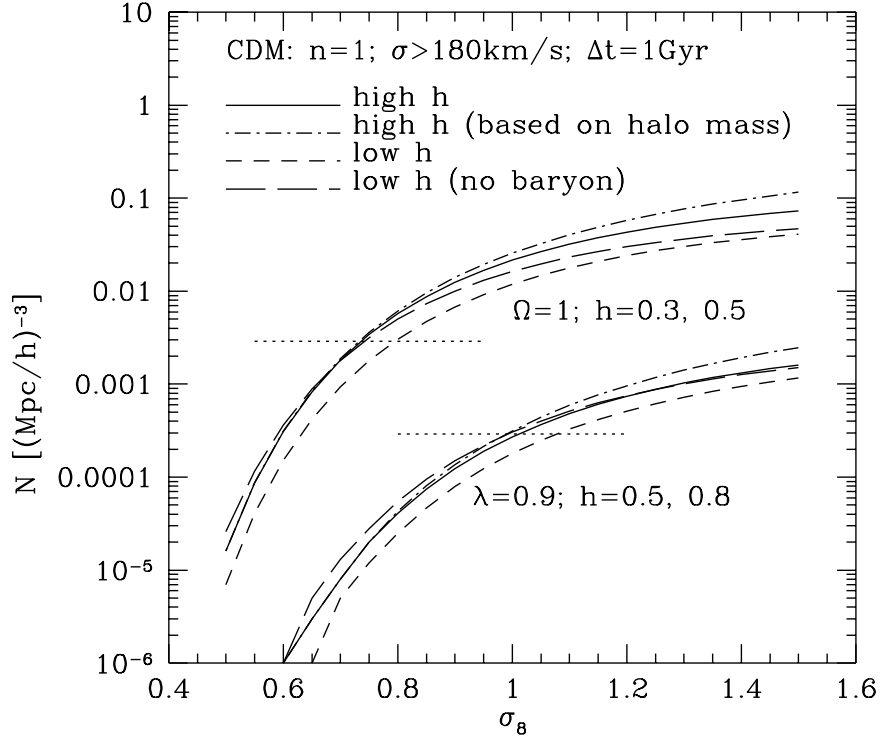


Fig. 1.— Comoving number densities of halos at  $\Delta t = 1 \text{ Gyr}$  before the epoch of  $z = 3$  predicted by the standard CDM model ( $\Omega_0 = 1$ ) and by a CDM model in a flat universe ( $\Omega_0 = 0.1$ ,  $\lambda_0 = 0.9$ ). For each model results are shown for two values of  $h$  (other parameters are fixed to be at their fiducial values), for one case where  $\Omega_b$  is set to be zero (for the lower  $h$  case only) and for a calculation using halo mass (see text). The horizontal dotted line shows the observed abundance of Lyman break galaxies (S96) estimated for the relevant cosmology.

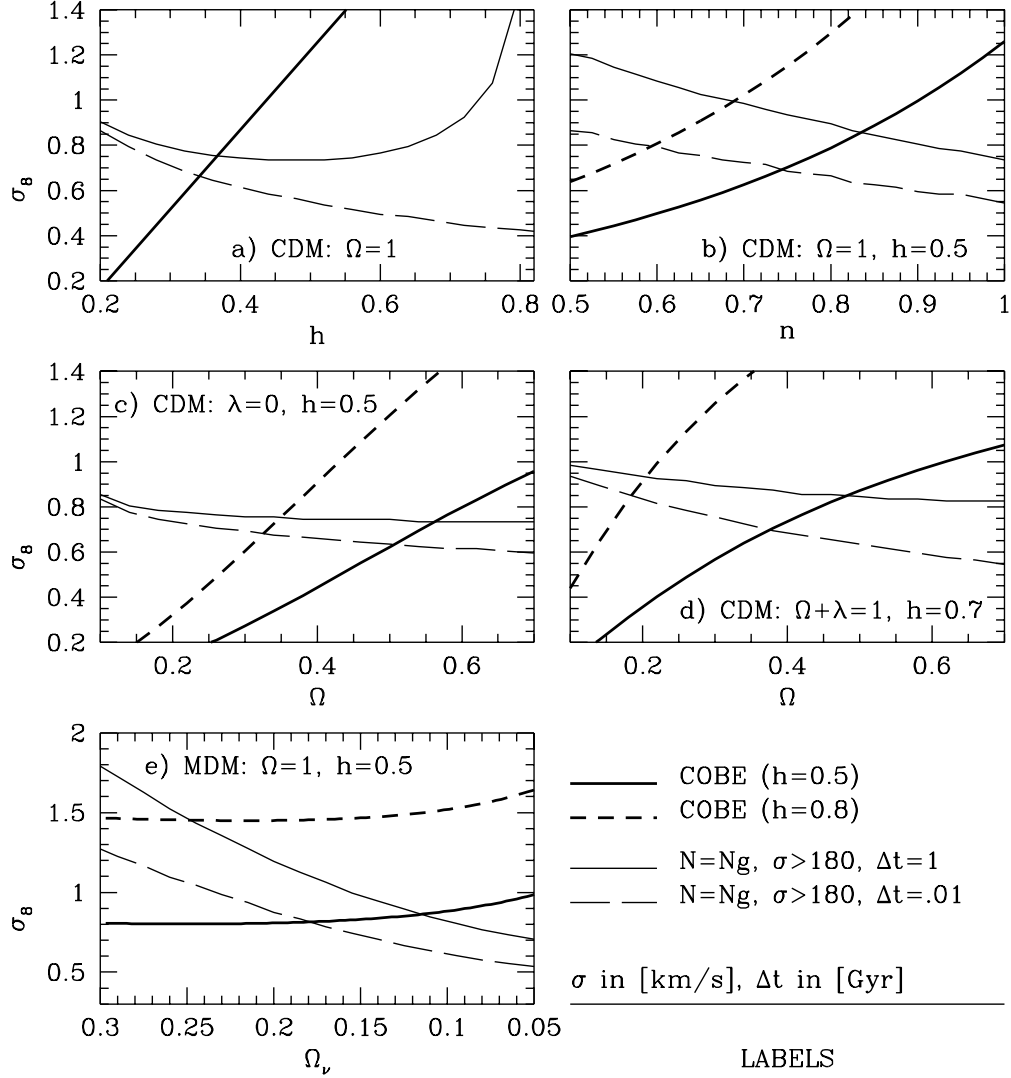


Fig. 2.— The values of  $\sigma_8$  required to have the predicted halo abundance to be equal to the observed abundance of Lyman break galaxies ( $N_g$ ). The value of  $\sigma_8$  given by the 4-year COBE data are also shown by thick curves (when two such curves are shown, they refer to two different  $h$ ). Since we require  $N \geq N_g$  (see text), the allowed region is below the curve indicating the COBE normalization (thick curves). Panels (a)-(d) are for CDM models, and (e) is for MDM models.

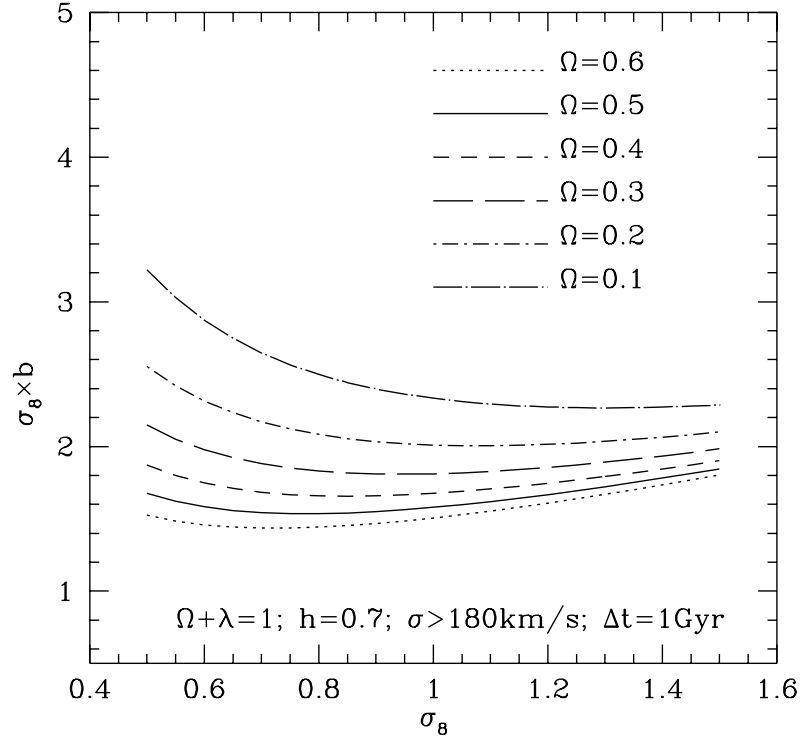


Fig. 3.— The bias parameter  $b$  (times  $\sigma_8$ ) for the halos of ‘Lyman break galaxies’ in flat models with various  $\Omega_0$  and  $\sigma_8$ . A value of  $\sigma_8 \times b > 1$  means that these ‘galaxies’ are more strongly correlated than present day normal galaxies.

Table 1. Model Parameters

model	$h$	$n$	$\Omega_0$	$\lambda_0$	$\Omega_\nu$
standard CDM	varying	1.0	1.0	0.0	0.0
tilted CDM	0.5	varying	1.0	0.0	0.0
open CDM	0.5-0.8	1.0	varying	0.0	0.0
flat CDM	0.5-0.8	1.0	$1 - \lambda_0$	varying	0.0
MDM	0.5	1.0	1.0	0.0	varying